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Wake of two interacting circular cylinders: A review

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ABSTRACT

The study of two cylinders in crossflow is of both fundamental and practical importance. There has been a surge in research interest in the last decade dedicated to this flow. Two reviews have been conducted on this topic by Zdravkovich (1977) and Sumner (2010), respectively. While the former was published more than 30 years ago, the latter is an excellent collection of past investigations. This paper provides a compendium of previous studies from a perspective distinct from both Zdravkovich (1977) and Sumner (2010). There is no doubt that the wake of two cylinders is highly complicated, depending on both centre-to-centre spacing and orientation of the two cylinders with respect to incident flow as well as Reynolds number. In this review, the full picture of the flow is provided in terms of a number of regimes. The physical aspects in each regime are discussed in detail, covering the flow structures, Strouhal numbers, fluid forces, heat and momentum transport characteristics, and Reynolds number effect.

1. Introduction

Cylindrical structures in arrays are frequently seen in engineering. Typical examples include offshore structures, marine risers, a group of chimney stacks, tubes in heat exchangers, bridge piers, stays, masts, chemical reaction towers and closely separated skyscrapers. The fluid forces and predominant vortex frequencies are the major considerations in the design of the engineering structures. Both steady and unsteady fluid forces acting on the structures are linked to the characteristics of the flow structure. The alternate vortex shedding from the structures and impinging upon the downstream structures may produce a large fluctuating pressure on the structures, causing structural vibrations, acoustic noise, and even resonance, which can trigger structural failure. Numerous failures in the practical applications of cylindrical structures in cross flow are illustrated in Chen (1987a, 1987b), Paidoussis (1979, 1981, 1983, 1993) and Blevins (1990). The cost associated with a typical engineering structural failure can easily reach the order of one million dollars and even billions of dollars. Naturally, there is a pressing need to study and to understand the fluid dynamics associated with multiple cylindrical structures in cross flow.

Two parallel cylinders are considered to be the simplest configuration of one array of cylinders (Fig. 1). Fluid-dynamic interference between two cylinders may give rise to flow separation, gap flow switching, shear-layer development, reattachment, vortex impingement, recirculation, quasi-periodic vortices and vortex street interaction, involving most of the generic flow features associated with multiple structures. Thus, flow around two cylinders provides an excellent model for gaining insight into the underlying flow physics around more structures and the study of the two cylinder wake has gained a momentum in the past four decades, as is evident from the distribution of relevant publications collected largely from archival journals since 1930 (Fig. 2a). While the number of experimental investigations is almost unchanged from the period of 1990–1999 to that of 2000–2009, there is a drastic growth in numerical simulation in 2000–2009 and the studies during this period account in number for 43% of the total in the literature, experimental and numerical works being 20% and 23%, respectively. Moving into this decade (2010–2020), experimental reports appear shrinking dramatically in number compared to the numerical, the latter being almost four times the former. The great increase in numerical investigations is apparently linked to the rapidly developing computing power in the past two decades.

There is an infinitely large number of possible configurations for two parallel cylinders. Each configuration is uniquely defined by the cylinder centre-to-centre spacing ratio P^* and the angle α between the freestream flow and the line connecting the centers of the cylinders (Fig. 1). In this review, a superscript asterisk denotes normalization by the cylinder diameter D and/or the freestream velocity U_∞. Two cylinders in the tandem and side-by-side arrangements are given by ($\alpha = 0°$, $P^* = L^*$) and ($\alpha = 90°$, $P^* = T^*$), respectively, where L and T are longitudinal and transverse separations, respectively, between the cylinder centres (Fig. 1a, b). The mutual interference between the cylinders in tandem is in general

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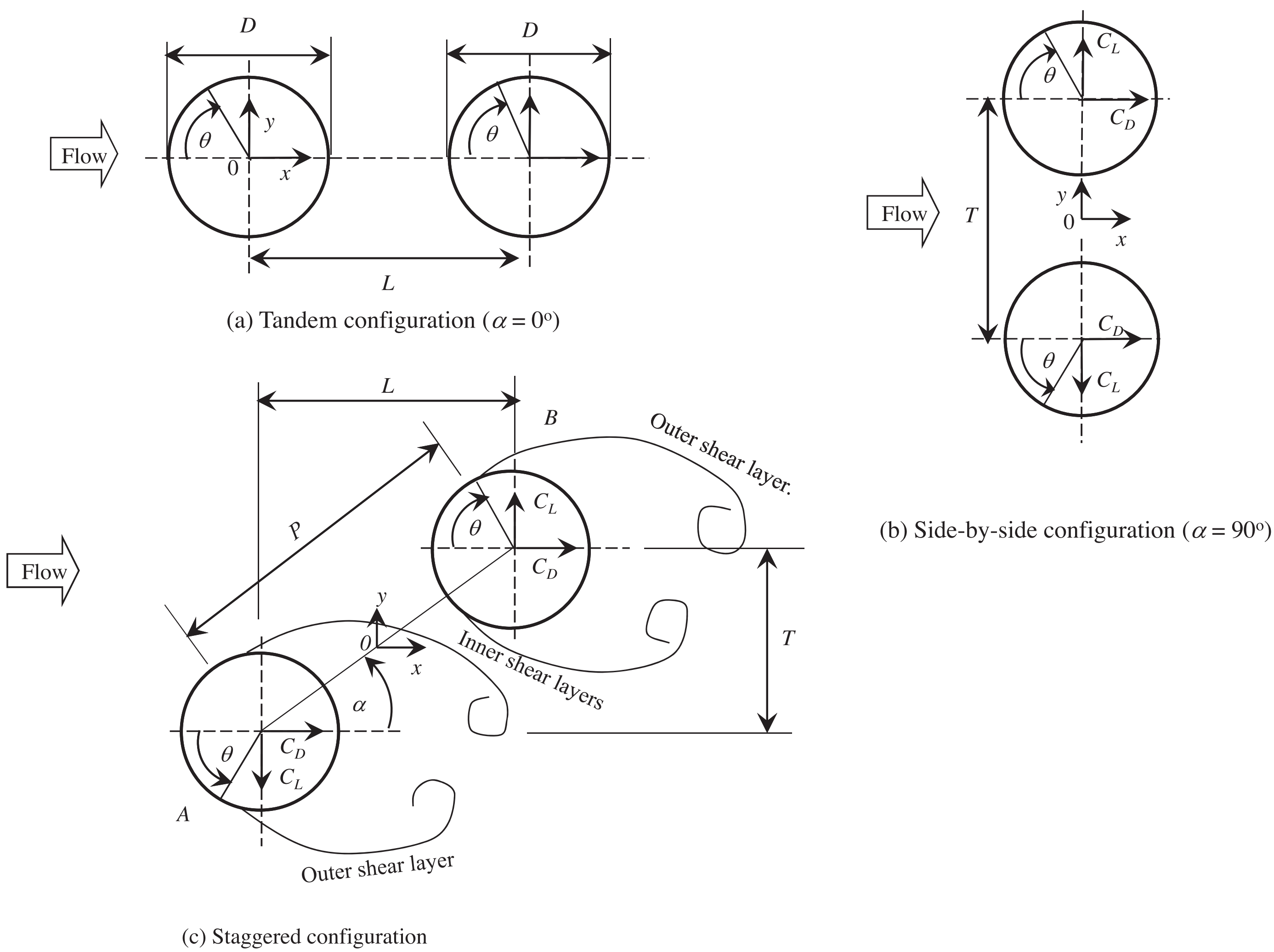

Fig. 1. Arrangements of cylinders and definitions of symbols. D: cylinder diameter; P: cylinder center-to-center spacing; x, y: Cartesian coordinate; L and T: streamwise and transverse separations between the cylinders, respectively; α: stagger angle; θ: azimuthal angle; C_D and C_L: time-mean drag and lift, respectively.

stronger than in the side-by-side arrangement (Hori 1959). As the cylinder interference depends strongly on α, P^* and the Reynolds number Re ($\equiv \rho D U_\infty/\mu$, where ρ and μ are the density and viscosity of fluid, respectively), the characteristics of fluid dynamics such as the drag and lift coefficients, pressure coefficient distributions, Strouhal numbers St ($\equiv f_s D/U_\infty$, where f_s is the predominant vortex frequency) and flow structure all vary with the three governing parameters.

Zdravkovich (1977) and Sumner (2010) each conducted a thorough review of the previous studies of the various configurations of the flow. While the former was published 39 years ago, the latter is an excellent collection of past investigations. Our understanding of this flow has been developed largely based on experimental and numerical investigations, conducted over essentially the entire Re range reported in the literature and a low Re range, respectively. The Reynolds numbers involved can be supercritical and subcritical. The latter may be further divided into the low ($Re < 10^3$), intermediate ($Re = 1.0 \times 10^3 - 1.0 \times 10^4$) and high subcritical Re ranges ($Re = 1.0 \times 10^4 - 3.5 \times 10^5$). Fig. 2 (b) presents the distribution of past investigations for different Re ranges. The numerical data summarized in Table 1 have been obtained mostly at the low subcritical Re range in the last decade (Fig. 2a). In this Re range, there is also a considerable number of experimental studies (Table 2). About 50% of experimental studies are performed in the high subcritical Re range, a collection of which is given in Table 3. The number of investigations is much smaller at the intermediate subcritical Re (Table 4) than at the high subcritical Re. Measurements are very limited in the supercritical flow regime (Table 5, $Re > 3.5 \times 10^5$), accounting in number for only about 3% of the total investigations presently collected, despite the fact that the flow of the supercritical Re is more practical in civil, mechanical and electrical engineerings. This is apparently because it is not easy to achieve such high Re in wind tunnels. Okajima (1979) achieved at $Re = 2 \times 10^5$ a similar flow to that at $Re = 6.2 \times 10^5$ via adding roughness on the cylinder surface to promote an early transition to turbulence in the boundary layers of the cylinders. Gu et al. (1993) attained the supercritical flow at a high incident turbulent intensity $T_u = 10\%$.

Various aspects of the flow have been investigated in the past, including the velocity field (VF) or flow structure (FS) captured from flow visualization, St, time-averaged pressure coefficient C_P, drag C_D and lift C_L, fluctuating or root mean square (rms) pressure coefficient $C_P{}'$, drag $C_D{}'$ and lift $C_L{}'$. Fig. 2 (c) presents the percentage distribution of individual aspects investigated in the publications, as listed in Tables 1– 5. Evidently, a great attention is given to VF + SF, St, C_D, C_L, and C_P, while considerably less is paid to $C_P{}'$, $C_D{}'$ and $C_L{}'$. This is perhaps because VF + SF, St, C_D, C_L, and C_P are relatively easy to measure using, e.g. PIV, hotwire, load cell, pressure transducer, and $C_P{}'$, $C_D{}'$ and $C_L{}'$ are more demanding for the measurement instrument and effort, being highly dependent

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